Patent Application

of

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for

Apparatus and Method for Optical Characterization of a Sample Over a Broadband of Wavelengths While Minimizing Polarization Changes

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is co-filed with application "Apparatus and Method for Optical Characterization of a Sample Over a Broadband of Wavelengths With a Small Spot Size" by Ray Hebert, Marc Aho and Abdul Rahim Forouhi, which is herein incorporated by reference.

FIELD OF THE INVENTION

The present invention relates generally to an apparatus and method for optically characterizing the properties of a sample on reflection and transmission of light over a broadband of wavelengths while minimizing polarization changes.

BACKGROUND OF THE INVENTION

Advances in microelectronics necessitate components with ever smaller critical dimensions. Manufacturing such components requires the use of shorter wavelengths of light in the lithography processes employed in component fabrication. This, in turn, has lead to a need to measure the optical characteristics of samples such as, among other, photolithographic masks and fabricated components over a broad range or broadband of wavelengths including the UV. Typically, in these measurements the cross-sectional diameter of a beam of light focused on the sample is large enough to spatially average the optical characteristic being measured yet small enough to resolve spatial variations across the sample. As the critical dimensions have decreased so too has the required diameter of the beam of light on the sample. It is now desirable to have a diameter of less than 100 micron.

As with many engineering problems, the design of an optical system to measure the optical characteristics of such a sample represents a tradeoff. For example, when illuminating the beam of light with the broadband of wavelengths from a light source onto a surface of the sample, it is desirable to have a small spot size but not a diffraction limited spot. In addition, this should be accomplished in an optically efficient manner. There

is, therefore, a tradeoff in this regard between a need for optical components with a low f-number (for higher optical efficiency) and a need for optical components with a high f-number (for a small spot size over a practical depth of field with minimal aberration and angles of incidence) and thus a small cone of rays corresponding to the beam of light that is used in the optical system, i.e., the useful light. Similar design tradeoffs occur in the collection and illumination on a detector of the beam of light reflected from the sample and the beam of light transmitted through the sample.

The need to operate over the broadband of wavelengths is a further design constraint for with many optical components because they are subject to a variety of effects such as chromatic aberration and absorption. For refractive optical components these effects become pronounced as the wavelengths approach the UV. There exist optical systems based on refractive optical components in the prior art that operate over a broadband of wavelengths with a small diameter of the beam of light on the sample. In these systems, attempts are made to compensate for chromatic aberration and absorption effects. However, this adds expense and complexity to these optical systems.

Reflective optical components are a suitable solution to this technical challenge. A wide variety of components are available including mirrors with non-spherical shape, such as an off-axis paraboloid shape, henceforth called an off-axis parabolic mirror. However, non-spherical shaped mirrors can add expense to the optical system, especially when such mirrors are manufactured by diamond turning. Optical systems including

torroidal, spherical and elliptical mirrors are disclosed in the prior art. For examples, see US 5,910,842, US 6,583,877 and US 6,128,085.

In addition, many prior art broadband optical systems combine refractive and reflective optical components. However, such catadioptric systems do not avoid the complexity and expense needed to overcome the chromatic aberration and absorption issues associated with refractive optical components.

Furthermore, when different samples are characterized, the beam of light in the optical system will need to be focused on the sample to correct for effects such as varying surface topography. Such an adjustment is problematic if the adjustment of the position of certain optical components in the optical system necessitates the adjustment of the position of many other optical components, since this can easily lead to misalignment. A preferred solution would allow the beam of light to be focused on the sample by adjusting a minimum number of components in the optical system or a simple assembly of components. Furthermore, such a preferred solution would be a sufficiently compact and simple optical system that a single light source could be used to optically characterize the reflection and transmission properties of the sample.

Addition information in the optical characterization of the sample can be obtained by selectively polarizing the beam of light illuminating the sample, analyzing the polarization of the beam of light reflected off of or transmitted through the sample, or both. This poses yet another technical challenge, since it is known that the polarization of the beam of light is changed on reflection from or transmission through materials.

It would be beneficial if such polarization changes associated with the optical components and the sample substrate could be minimized.

There is a continued need, therefore, for a compact optical system for optical characterization of a sample, which operates over a broadband of wavelengths with a small diameter of the beam of light on the sample and which employs reflective optics with a minimum number of optical components such that advantageous components such as off-axis parabolic mirrors can be used. There is also a need for such an optical system that can be focused by adjusting the position of the minimum number of optical components or a simple assembly of components, and for an optical system that minimizes changes in the polarization of the beam of light.

OBJECTS AND ADVANTAGES

In view of the above, it is a primary object of the present invention to provide an apparatus and method that enables optical characterization of the properties of a sample on reflection and transmission of a beam of light over a broadband of wavelengths with a small spot size on the surface of the sample while minimizing changes in the polarization of the light. More specifically, it is an object of the present invention to provide a broadband apparatus with a small spot size on the surface of the sample, and a method of using this apparatus, for optical characterization of the properties of the sample on reflection and transmission of the beam of light through the use of optical light paths comprising reflective optical components, including off-axis parabolic mirrors, which

minimize changes in the polarization of the beam of light. It is a further object of the present invention to provide an apparatus, and a method of using this apparatus, where the spot size on the surface of the sample can be brought into focus without extensive adjustment of the position of these optical light paths.

These and numerous other objects and advantages of the present invention will become apparent upon reading the following description.

SUMMARY

The objects and advantages of the present invention are secured by an apparatus and method for the optical characterization of the properties of a sample on reflection and transmission of a beam of light, with a small spot size on the sample, over a broadband of wavelengths. A broadband beam of light from a light source is fractionally magnified and illuminated onto a top surface of the sample. A portion of the broadband beam of light is reflected from the top surface of the sample, a portion of the broadband beam of light is transmitted through the sample and a portion of the broadband beam of light is absorbed. The portion of the broadband beam of light reflected from the top surface of the sample is redirected and illuminated onto a first detector. The portion of the broadband beam of light transmitted through the sample is redirected from a bottom surface of the sample and illuminated onto a second detector. These functions are accomplished using an illumination optical light path, a reflection optical light path and a transmission optical light path, each of which comprises reflective optical

components, thereby eliminating chromatic aberrations from these components. Pairs of planar and off-axis parabolic mirrors are used to redirect and magnify the broadband beam of light. In a preferred embodiment, the planar and off-axis parabolic mirrors are coated with a UV-enhancing aluminum coating. The broadband beam of light in the illumination optical light path, the reflection optical light path and the transmission optical light path is collimated between the pair of parabolic mirrors in each optical light path. This configuration allows focusing of the broadband beam of light on the top surface of the sample by adjusting a position of one of the pairs of planar and off-axis parabolic mirrors without requiring adjustment of the position of other components in each of the optical light paths.

In a preferred embodiment, polarization changes in the beam of light in the illumination optical light path, the reflection optical light path and the transmission optical light path are minimized by ensuring that angles of incidence and reflection of the broadband beam of light from the planar and off-axis parabolic mirrors in each of the light paths are small (near the normal to the mirrors) and that the angles in the beam of light illuminated on, reflected from or transmitted through the sample are near normal to the top surface or the bottom surface of the sample.

In another embodiment of this invention, an optical fiber is used to redirect the portion of the broadband beam of light transmitted through the sample to illuminate the second detector.

In another embodiment of this invention, a polarizing means is incorporated into at least one of the optical light paths to adjust the polarization of the broadband band beam of light.

In another embodiment of this invention, the portion of the broadband beam of light reflected from the sample and the portion of the broadband beam of light transmitted through the sample are each redirected and illuminated onto a common detector.

A detailed description of the invention and the preferred and alternative embodiments is presented below in reference to the attached drawing figures.

BRIEF DESCRIPTION OF THE FIGURES

Fig. 1 is a diagram illustrating an apparatus according to the invention.

Fig. 2 is a diagram illustrating another embodiment of an apparatus according to the invention.

Fig. 3 is a diagram illustrating a side view of one of the planar mirrors of the apparatus in Fig. 1 or Fig. 2.

Fig. 4 is a diagram illustrating a side view of one of the off-axis parabolic mirrors of the apparatus in Fig. 1 or Fig. 2.

Fig. 5 is a diagram illustrating the focusing of the broadband beam of light onto the sample surface.

Fig. 6 is a diagram illustrating a cross-sectional view of the broadband beam of light.

Fig. 7. is a diagram illustrating the beam of light incident, reflected and transmitted from a surface with the

polarization of the light perpendicular to the plane defined by the incident and reflected light.

Fig. 8 is a diagram illustrating the beam of light incident, reflected and transmitted from a surface with the polarization of the light in the plane defined by the incident and reflected light.

Fig. 9 shows the calculated amplitude coefficient as a function of the angle of incidence for light incident in air onto an aluminum object.

DETAILED DESCRIPTION OF THE EMBODIMENTS

A preferred embodiment of the invention is illustrated in Fig. 1. An apparatus **100** according to the invention comprises a first optical light path **110**, a second optical light path **160** and a third optical light path **180**. A light source **112** produces the broadband beam of light **114** between 190 nm and 1100 nm (broadband beam **114** is identified by its extremal rays in Fig. 1). An arc source, such as a Hamamatsu L2-2000 series deuterium lamp, is suitable for the UV portion of the spectrum, and a tungsten lamp for the visible and IR portions of the spectrum. A combination of the deuterium lamp and the tungsten lamp is suitable as the light source **112**. The broadband beam of light **114** is redirected on reflection off of a first planar mirror **116**. A model 01-MGF-005/028 planar mirror from Melles-Griot is suitable as the planar mirror **116**.

Referring to Fig. 3, the broadband beam of light **114** has a maximum angle of incidence **120** relative to a normal **118** to the planar mirror **116** and a maximum angle of reflection **122** relative to the normal **118** of the planar mirror **116**. By keeping the maximum angle of incidence **120** and the maximum angle of

reflection **122** small, that is, negligible with respect to the normal **118**, changes in the polarization of the broadband beam of light **114** are minimized. The same technique is used for planar mirrors **138**, **164**, **170**, **190** and **196** in the apparatus. This technique is further described in Figs. 7-9.

Referring to Fig. 7, two regions, **300** and **302** are separated by a surface **304**. There is incident light **312**, with an angle of incidence **326** relative to a normal **306**, reflected light **318**, with an angle of reflection **328** relative to the normal **306**, and transmitted light **324**, with an angle of transmission **330** relative to the normal **306**. The electric field **308** in incident light **312**, the electric field **314** in reflected light **318** and the electric field **320** in transmitted light **324** are directed perpendicular to the plane defined by the incident light **312** and the reflected light **318**. The incident light **312** has a magnetic field **310**, the reflected light **314** has a magnetic field **316** and the transmitted light **324** has a magnetic field **322**. Referring to Fig. 8, in an alternate polarization the electric field **332** in the incident light **312**, the electric field **336** in the reflected light **318** and the electric field **340** in the transmitted light **324** are directed in the plane defined by the incident light **312** and the reflected light **318**. The incident light **312** has a magnetic field **334**, the reflected light **318** has a magnetic field **338** and the transmitted light **324** has a magnetic field **342**. For this geometry, any electric field polarization can be obtained by the linear superposition of the electric field polarizations shown in Figs. 7 and 8. Thus, it is sufficient to consider the impact of reflection and transmission for these two polarizations.

Referring to Fig. 9, the calculated amplitude coefficients using Fresnel's equations for light, in a medium in region **300** with an index of refraction of 1.0, reflected off of and transmitted through aluminum in region **302**, with an index of refraction of 1.39, as a function of the angle of incidence **326** is shown. The four amplitude coefficients are $r_{||}$, $r_{\perp}$, $t_{||}$ and $t_{\perp}$, where $r_{||}$ and $t_{||}$ is the ratio of the parallel component of the electric field **336** in the reflected light **318** and the parallel component of the electric field **340** in the transmitted light **324** relative to the parallel component of the electric field **332** in the incident light **312**, and $r_{\perp}$ and $t_{\perp}$ is the ratio of the perpendicular component of the electric field **314** in the reflected light **318** and the perpendicular component of the electric field **320** in the transmitted light **324** relative to the perpendicular component of the electric field **308** in the incident light **312**. As shown in Fig. 9, the amplitude coefficients, and thus the polarization of the light, are substantially unchanged for angle of incidence **326** (and, by symmetry, for angle of reflection **328**) substantially less than 30 degrees from the normal **306** to the surface **304**. The result that the polarization is substantially unchanged for angle incidence **326** (angle of reflection **328**) negligible with respect to the normal **306** to the surface **304** is unchanged for values of the index of refraction in region **302** substantially the same as that used in the calculation shown in Fig. 9.

Referring back to Fig. 1, the first planar mirror **116** is positioned relative to a first off-axis parabolic mirror **126** such that the broadband beam of light **114** is collimated on reflection from the first off-axis parabolic mirror **126**. A

suitable off-axis parabolic mirror can be custom manufactured by Edmond Industrial Optics using diamond turning. A commercially available example of such an off-axis parabolic mirror is model H47-085 from Edmond Industrial Optics. Referring to Fig. 4, the broadband beam of light **114** has a maximum angle of incidence **130** and a maximum angle of reflection **132** relative to a normal **128** to the off-axis parabolic mirror **126**. By keeping the maximum angle of incidence **130** and the maximum angle of reflection **132** small, that is, negligible with respect to the normal **128**, changes to the polarization of the broadband beam of light **114** are minimized. The same technique is used for off-axis parabolic mirrors **140**, **162**, **168**, **188** and **194** in the apparatus.

Referring back to Fig. 1, the broadband beam of light **114** is redirected on reflection off of a second planar mirror **138**. The broadband beam of light **114** incident and reflected off of the second planar mirror **138** is collimated. The second planar mirror **138** is positioned relative to a second off-axis parabolic mirror **140** such that the broadband beam of light **114** illuminates and is brought into focus on a sample **144**.

Referring to Fig. 5, the broadband beam of light **114** is collimated when incident on the second off-axis parabolic mirror **140**. This ensures that the broadband beam of light **114** will come to focus at a distance **142** from the second off-axis parabolic mirror **140**. There is a known relationship between the distance **142** and focal length along axis of the second off-axis parabolic mirror **140**. A person of skill in the art will be able to determine the focal length from the curvature of the second off-axis parabolic mirror **140**. By adjusting the position of the second off-axis parabolic mirror **140** relative to the sample **144**,

the broadband beam of light **114** is brought into focus on a top surface **146** of the sample **144**. It is important, however, that the position of the second planar mirror **138** be adjusted such that the second planar mirror **138** maintains the same position relative to the second off-axis parabolic mirror **140**. In this way, the collimated light reflected off of the second planar mirror **138** remains parallel to the axis (not shown) of the second off-axis parabolic mirror **140**. Since the broadband beam of light **114** incident on the second planar mirror **138** is collimated, this adjustment of the position of the second planar mirror **138** and the second off-axis parabolic mirror **140** does not necessitate adjustment of the position of the other components in the first optical light path **110**.

Referring to Fig. 6, the broadband beam of light **114** has a cross-section **210** with a diameter **220** defined as twice the distance from the center of the cross-section **210** where the light intensity is reduced by a factor of 1/e. The broadband beam of light **114** has a diameter **220** greater than 500 microns at the light source **112** and a diameter **220** between 50 microns and 80 microns on the top surface **146** of the sample **144**. This reduction is proportional to the ratio of the focal lengths of off-axis parabolic mirror **140** and off-axis parabolic mirror **126**.

Referring back to Fig. 5, the small diameter **220** of the broadband beam of light **114** illuminated on the top surface **146** of the sample **144** corresponds to a small spread of angles in the cone of rays in the broadband beam of light **114** incident on the sample **144**. The broadband beam of light **114** incident on the top surface **146** of the sample **144** has a minimum angle of incidence **152** and a maximum angle of incidence **154** relative to a normal

150 to the top surface **146** of the sample **144**. By keeping the maximum angle of incidence **154** small, that is, negligible with respect to the normal **150**, changes to the polarization of the broadband beam of light **114** are minimized.

Referring back to Fig. 1, the broadband beam of light **161** is reflected from the top surface **146** of the sample **144** (broadband beam **161** is identified by its extremal rays in Fig. 1). The broadband beam of light **161** is redirected and magnified in the second optical light path **160**. The broadband beam of light **161** is redirected on reflection off of a first off-axis parabolic mirror **162** and then redirected on reflection off of a first planar mirror **164**. In a manner similar to that used in adjusting the position of second planar mirror **138** and second off-axis parabolic mirror **140** in the first optical light path **110**, the position of the first off-axis parabolic mirror **162** and the first planar mirror **164** relative to the top surface **146** of the sample **144** are adjusted such that the broadband beam of light **161** incident and reflected from the first planar mirror **164** is collimated. This ensures that the adjustment of the position of the first off-axis parabolic mirror **162** and the adjustment of the position of the first planar mirror **164** does not necessitate adjustment of the position of other components in the second optical light path **160**. Referring back to Fig. 5, the small diameter **220** of the broadband beam of light **114** on the top surface **146** of the sample **144** corresponds to a small spread of angles in the cone of rays in the broadband beam **161** of light with a minimum angle of reflection **156** and a maximum angle of reflection **158**. By keeping the maximum angle of reflection **158** small, that is, negligible with respect to the normal **150**,

changes to the polarization of the broadband beam of light **161** are minimized.

Referring back to Fig. 1, the broadband beam of light **161** is redirected on reflection off of a second of-axis parabolic mirror **168**. The broadband beam of light **161** is redirected on reflection off of the second planar mirror **170** and illuminates a first detector **172**. The entrance aperture **171** of the first detector **172** is positioned at the focal length of the second off-axis parabolic mirror **168**. A person of skill in the art will be able to determine the focal length from the curvature of the second off-axis parabolic mirror **168**.

Referring back to Fig. 5, after transmission through the sample **144** the broadband beam of light **181** exits the sample through a bottom surface **148** of the sample **144** (broadband beam **181** is identified by its extremal rays in Fig. 5). The cone of rays in the broadband beam of light **181** transmitted through the sample **144** has minimum angle of transmission **184** and maximum angle of transmission **186** relative to a normal **182** to the bottom surface **148** of the sample **144**. By keeping the maximum angle of transmission **186** small, that is, negligible with respect to the normal **182**, changes to the polarization of the broadband beam of light **181** are minimized. Referring back to Fig. 1, the broadband beam of light **181** is redirected and magnified by the third optical light path **180**. The broadband beam of light **181** is redirected on reflection off of a first off-axis parabolic mirror **188** and then redirected on reflection off of a first planar mirror **190**. In a manner similar to that used in adjusting the position of second planar mirror **138** and second off-axis parabolic mirror **140** in the first optical light path

110, the position of the first off-axis parabolic mirror **188** and the first planar mirror **190** relative to the top surface **146** of the sample **144** are adjusted such that the broadband beam of light **181** incident and reflected from the first planar mirror **190** is collimated. This ensures that the adjustment of the position of the first off-axis parabolic mirror **188** and the adjustment of the position of the first planar mirror **190** does not necessitate adjustment of the position of other components in the third optical light path **180.** Since the broadband beam of light **114, 161** and **181** is collimated substantially perpendicular to the sample **144** over a portion of the first optical light path **110,** the second optical light path **160** and the third optical light path **180,** in an embodiment of this invention the adjustment of the second planar mirror **138** and second off-axis parabolic mirror **140,** the first off-axis parabolic mirror **162** and the first planar mirror **164,** and the first off-axis parabolic mirror **188** and the first planar mirror **190** relative to the top surface **146** of the sample **144** is accomplished with a group of mechanically coupled elements. The broadband beam of light **181** is redirected on reflection off of a second of-axis parabolic mirror **194.** The broadband beam of light **181** is redirected on reflection off of the second planar mirror **196** and illuminates a second detector **198.** The entrance aperture **197** of the second detector **198** is positioned at the focal length of the second off-axis parabolic mirror **194.** A person of skill in the art will be able to determine the focal length from the curvature of the second off-axis parabolic mirror **194.**

Fig. 3 illustrates a side view of the first planar mirror **116** in the first optical light path **110**. In a preferred embodiment of the invention, the planar mirror **116** includes a UV-enhancing aluminum coating **124**. As an example, the model 01-MGF-005/028 planar mirror from Melles-Griot has a UV-enhancing aluminum coating **124**. In a preferred embodiment, such UV-enhancing aluminum coatings are used on the other planar mirrors **138, 164, 170, 190** and **196** in the first optical light path **110,** the second optical light path **160** and the third optical light path **180.**

Fig. 4 illustrates a side view of the first off-axis parabolic mirror **126** in the first optical light path **110.** In a preferred embodiment of the invention, the off-axis parabolic mirror **126** includes a UV-enhancing aluminum coating **134.** Edmond Industrial Optics is a supplier of such UV-enhanced aluminum coatings. In a preferred embodiment, such UV-enhancing aluminum coatings are used on the other off-axis parabolic mirrors **140, 162, 168, 188** and **194** in the first optical light path **110,** the second optical light path **160** and the third optical light path **180.**

Fig. 2 illustrates alternate embodiments of the invention. The first optical light path **110** includes a polarizing means **136** for polarizing the broadband beam of light **114** in one of two orthogonal directions. A suitable device is a model PTH-SMP Glan Thompson-type calcite polarizer made by Harrick. The second optical light path **160** includes a polarizing means **166,** such as a polarizing analyzer. Once again, the model PTH-SMP Glan Thompson-type calcite polarizer made by Harrick is

suitable. The third optical light path **180** includes a polarizing means **192**, such as a polarizing analyzer.

In another embodiment of this invention, the third optical light path **180** also includes an optical fiber **199** for redirecting the broadband beam **181** from the third optical light path **180** to the second detector **198**.

In another embodiment of this invention, the broadband beam **181** from the third optical light path **180** is redirected and illuminated onto the first detector **172** eliminating the need for the second detector **198**. Additional optical components, such as a beam splitter, may be added as is known in the art to ensure that broadband beam **161** and broadband beam **181** are coaxial when they illuminate the first detector **172**. A chopper may also be added.

Referring back to Fig. 1, the first detector **172** and the second detector **198** depend on the type of optical characterization to be performed on the sample **144**. For measurements of reflected or transmitted intensity as a function of wavelength, the first detector **172** and the second detector **198** with a monochromator, a diode array or a photomutiplier tube is suitable. A monochromator with a 512-element diode array (Model PDA-512) is available from Control Development. A mechanically scanned monochromator is known in the art. A suitable photomultiplier is model R928 from Hamamatsu. For a spectroscopic ellipsometer, a polarization analyzer, such as the model PTH-SMP Glan Thompson-type calcite polarizer made by Harrick, in addition to the monochromator, the diode array or the photomultiplier tube is suitable. In one embodiment, the polarization analyzer can be incorporated in the first detector

172 and the second detector **198**. The analysis techniques in United States patent US 4,905,170 to Forouhi et al. and United States patent application US 10/607,410 to Li et al., hereby incorporated by reference, can be used to determine optical characteristics of the sample **144** from the measurements.

By employing substantially reflective optical components and off-axis parabolic mirrors with collimated incident broadband beam of light **114**, reflected broadband beam of light **161**, and transmitted broadband beam of light **181**, the invention minimizes chromatic aberration in the first light path **110**, the second light path **160** and the third light path **180**. This enables the small diameter **220** of the broadband beam of light **114** and **161** on the top surface **146** of the sample **144** as well as optical characterization of reflection and transmission properties using the single light source **112**. The diameter **220** of the broadband beam of light **114** and **161** is small enough to resolve spatial variations in optical characteristics on the top surface **146** of the sample **144** yet large enough to spatially average the optical characteristics of the sample **144**. Artifacts associated with diamond-turned parabolic mirrors are not a concern in this invention since the diameter **220** of the broadband beam of light **114** and **161** on the top surface **146** and the diameter **220** of the broadband beam of light **181** on the bottom surface **148** of the sample **144** are not diffraction limited. The principle impact of such artifacts is scattering of the broadband beam of light **114**, **161** and **181**, which is not a concern in this invention since these scattered rays will not be illuminated onto the first detector **172** or the second detector **198**.

Furthermore, by ensuring that the maximum angle of incidence **120** and reflection **122** for the planar mirrors **116, 138, 164, 170, 190** and **196** are small, that is, negligible with respect to the normal **118**, that the maximum angle of incidence **130** and reflection **132** for the off-axis parabolic mirrors **126, 140, 162, 168, 188** and **194** are small, that is, negligible with respect to the normal **128**, that the maximum angle of incidence **154** and the maximum angle of reflection **158** from the top surface **146** are small, that is, negligible with respect to the normal **150**, and that the maximum angle of transmission **186** is small, that is, negligible with respect to the normal **182** to the bottom surface **148** changes to the polarization of the broadband beam of light **114, 161** and **181** are minimized.

The first, second and third optical light paths **110, 160** and **180** in this invention have been described with parabolic mirrors **126, 140, 162, 168, 188** and **194**. One skilled in the art will recognize that other mirror shapes such as a toroidal mirror as well as those based on conic sections, such as elliptical, hyperbolic and spherical, are also suitable. In addition, another reflective surface may be substituted for the planar mirrors **116, 138, 164, 170, 190** and **196**.

In view of the above, it will be clear to one skilled in the art that the above embodiments may be altered in many ways without departing from the scope of the invention. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.